

A Calorimeter for High-Power CW Lasers

RICHARD L. SMITH, THOMAS W. RUSSELL, WILLIAM E. CASE, AND ALVIN L. RASMUSSEN

Abstract—A calorimeter is described that can measure megajoules of laser energy from CW lasers whose output wavelength is in the region from 1 to 11 μm . The calibration of this device is traceable to NBS electrical standards. This calorimeter can measure total energies from 3×10^4 to 10^7 J. The laser power range this device can handle ranges from 300 to 100 000 W.

± 0.35 percent. The calibration factor for this device is 2.267×10^6 J/V, where 1 V corresponds to a temperature interval of approximately 12°C . The laser power that can be accommodated by this instrument ranges from about 300 to approximately 100 000 W. The laser energy must be entirely contained inside the aperture of this instrument, which is 10 cm in diameter.

I. INTRODUCTION

We wish to describe a calorimeter that has been constructed and calibrated at NBS that can measure megajoules of energy emitted by a CW laser whose output wavelength is in the region from 1 to 11 μm . The calibration of this device is traceable to NBS electrical standards. This method of calibrating calorimeters and power meters for the measurement of laser energy and power has been the object of a program conducted at NBS [1]. A calorimeter can be used to measure the total energy in a pulse, and if the time duration of the pulse is known, the average power can be computed.

It is well known that much less than a million joules is enough to do eye damage and destroy laser mirrors and optical components. One megajoule will melt about 180 cm^3 of copper, which corresponds to a surface layer 1 μm thick and 1340 cm on a side. The major difficulty in trying to deal with a megajoule is that it can cause surface damage. Therefore, the big problem of measuring megajoules is to get the energy absorbed and distributed through some volume before damage is done.

The general idea of the operation of the calorimeter is as follows: the laser radiation is absorbed in an optical cavity that is designed to have a high absorptance. Because of the large size of this device water is circulated through the walls of the calorimeter to distribute the heat in a reasonable time. A thermometer immersed in the water measures the temperature rise of the calorimeter. The calibration of the device is carried out by inserting into the calorimeter a known amount of electrical energy and determining the temperature rise for this known amount of energy. The output of the thermometer is an electrical signal, and since we do not need to work on any particular temperature scale, we obtained a calibration factor with units of joules per volt.

The calorimeter BB 1 that we wish to describe can measure energies from 3×10^4 to 10^7 J, and it can measure energies down to 3×10^3 J with larger uncertainty. The systematic error is estimated to be ± 2.6 per cent and the precision is

II. OPTICAL DESIGN

The main points that were considered in the optical design of this instrument were as follows: 1) to lower the local power density of the laser beam to a point such that it could be absorbed without damaging the absorbing surface; 2) to have only a very small amount of the incident radiation scattered out of the instrument.

Because the incident power density was believed to be too large for a direct absorption on a surface, it was decided to expand the beam in such a way that the average and peak power densities could be conveniently handled. A cross-sectional view of the structure settled on is shown in Fig. 1.

The entrance to the laser calorimeter is a square cone. A circular configuration was not used because such a structure produces a line focus of radiation near the exit of the cone going into the device. It was felt that such an increase in power density would be highly undesirable for the first mirror as well as for the possibly remote chance of causing air breakdown. The surfaces of the cone are optical surfaces that are gold coated. For the angle of incidence determined by this cone about 5 percent of the radiation striking its surfaces will be absorbed. Normally one would expect that less than half the total beam power would strike these surfaces. However, because of potential variations in the beam profile, the cone was designed to handle the total laser power on any one of its surfaces.

The main portion of the laser beam passes through the cone or horn and strikes the cylindrical mirror 1 of Fig. 1. This mirror also has vacuum-deposited gold on its surface. This mirror produces a diverging beam that strikes either an adjacent flat mirror 2 or a sand-blasted gold-coated copper plate 3. The light that strikes the flat mirror also continues on and strikes the sand-blasted plate. This plate scatters the radiation widely over the interior of the instrument. In the optimum design the remaining surfaces are black to the wavelength of the incident radiation.

The purpose of the cylindrical mirror is to reduce the incident power density and to direct the beam to the sand-blasted plate. The sand-blasted plate, by scattering the beam, reduces the laser power density to such a level that it can be safely absorbed by the remaining black surfaces.

Each surface has its own damage threshold, which depends

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The authors are with the Quantum Electronics Division, National Bureau of Standards, Boulder, Colo. 80302.

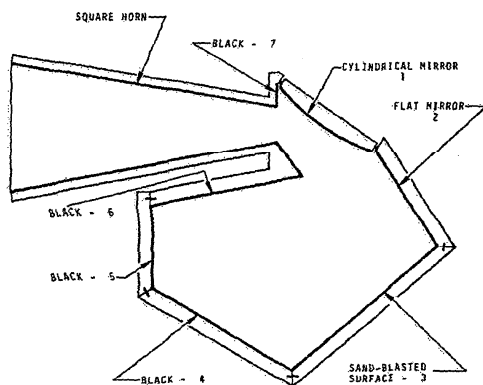


Fig. 1. Cross section of optical cavity of calorimeter.

upon a number of parameters. In most cases it depends upon whether the piece is cooled or whether it is in thermal isolation. Consider laser radiation impinging upon a metal surface. Part of this radiation is absorbed and converted to heat, while the remainder is reflected. The absorbed radiation causes a temperature increase of the surface. This results in heat flow in the metal away from the hotter region plus increased thermal radiation from the hot surface.

While a very high surface temperature is favorable for the rapid transportation of a large quantity of thermal energy by conduction, it is undesirable because of the increase in the thermal radiation from the surface and, more importantly, because the higher surface temperature is more likely to result in surface damage. Surface damage on a low-absorption surface can lead to increased absorption, then to more damage, and finally to a wall failure. For a black surface damage may decrease the absorption, thus increasing the possibility of more backscatter from the instrument.

Flowing water cools the metal walls of the calorimeter and distributes the energy in the calorimeter. In some very preliminary experiments on test samples of surfaces similar to the materials used in BB 1 it was found that the surface temperature rose about $0.3^{\circ}\text{C}/\text{W}/\text{cm}^2$ of absorbed power. If we wish to restrict the temperature rise of the surface to 100°C , we would limit the absorbed power density to $333 \text{ W}/\text{cm}^2$. For a rough rule of thumb, we used the value of $200 \text{ W}/\text{cm}^2$ as the maximum power we wanted absorbed on any surface. This we felt would not produce a 100°C temperature rise. If our design calculations suggested that power in excess of $200 \text{ W}/\text{cm}^2$ might be absorbed in some region we looked at the situation to see if that power would be dissipated without serious problems.

The total black area of this instrument is approximately 1100 cm^2 . If we absorbed $200 \text{ W}/\text{cm}^2$ this would allow us to absorb a total of $220\,000 \text{ W}$. However, because the radiation scattered from the sand-blasted surface will not intercept the absorbing surfaces with the same power density everywhere, one would expect a significant variation in the power density striking the black surface.

In the design of this instrument one would like to know a number of properties of the surfaces used. Normally one would like to know the absorption of the surface, the amount of scattering due to the surface, and the damage threshold of the surface. The literature contains almost no information on these quantities for surfaces that are practical for use in a high-power calorimeter. In most cases, the measuring of these quantities is a fairly involved task. Furthermore, to determine values for the damage threshold one must first have an energy meter operating at these power levels.

III. THERMAL DESIGN

The main thermal considerations were as follows: 1) to circulate water throughout the calorimeter so that the approach to thermal equilibrium is hastened; and 2) to thermally isolate the calorimeter from its environment. A 1-hp electrical motor outside the instrument was connected through an insulated shaft to a water pump located inside the shell surrounding the calorimeter. The motor and pump can be seen in Fig. 2 in the lower right-hand portion. This figure shows the calorimeter with one of its side panels removed. The cylindrical can in the approximate center is the water reservoir, which holds one electric heater and the Maier temperature-measuring bridge. The square frame with the circular opening that is to the left of center holds the optical cavity in place. The pipes that guide the water through the walls of the calorimeter are visible. In the water channels that are in the walls of the optical cavity is another set of electrical heaters. The entire calorimeter is surrounded by an aluminum frame covered with $\frac{1}{4}$ -in aluminum sheets. On the inside of these sheets was placed a layer of styrofoam about 2 in thick. The inner-surface of the styrofoam was covered with aluminum foil. The cylindrical object on the top of the calorimeter, which looks somewhat like a handle on a suitcase, is a C-series reference calorimeter [1]. BB 1 is about $2\frac{1}{2}$ ft high and about 5 ft long. It weighs about 400 lb.

The temperature is sensed by a resistance bridge as described by Maier [2]. The bridge consists of alternate arms of copper and manganin of about $100\text{-}\Omega$ resistance. The bridge balances at about 29°C . The bridge is supplied by a constant current of about 20 mA. The output of the bridge is amplified by a dc amplifier linear to better than 0.01 percent, and it has a gain of about 20. The output of the amplifier is read by a digital voltmeter. At equal intervals of 10 s the voltmeter reading is transferred to a data coupler and then printed by a typewriter that simultaneously punches a paper tape.

IV. THE THEORY OF THE MEASUREMENT

The BB 1 calorimeter is of the isoperibol type; that is, the theory assumes the calorimeter operates in an environment in which the temperature does not change with time. If this temperature varies appreciably it will cause the heat exchange term to be incorrectly determined. The theory for this type of calorimeter has been worked out in detail [1], [3]. The application of the theory to data reduction for temperatures taken at equal time intervals has been worked out for both a least squares computer program and a manual approxima-

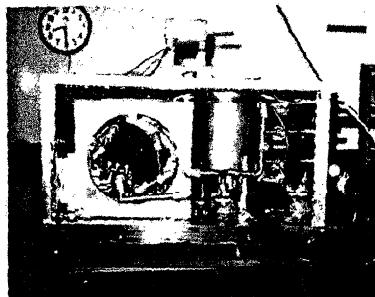


Fig. 2. BB 1 calorimeter with side panel removed.

tion [4]. The theory is summarized in the equation

$$W = E \left[T_R - T_I + \epsilon \int_{T_I}^{T_F} (T - T_\infty) dt \right] \quad (1)$$

where

- W thermodynamic work done on the calorimeter, either by a laser beam or by a calibrating electrical current,
- E energy equivalent, often called the calibration factor,
- T temperature,
- ϵ cooling constant (described later),
- t time.

The quantity in brackets is traditionally called the corrected temperature rise ΔT_c . The subscripts I and F refer to the initial and final rating periods, as outlined later. The initial and final temperatures must be observed during rating periods as defined by (2). The convergence temperature T_∞ is the temperature observed at an infinite time.

The other equation essential to the measurement is the following:

$$dT/dt = -\epsilon(T - T_\infty). \quad (2)$$

When the temperature obeys this equation, the calorimeter is said to be in a rating period. The measurement requires that rating periods both precede and follow the work input to the calorimeter. Two equations, one for each rating period, can be solved for the convergence temperature T_∞ and the cooling constant ϵ . The magnitude of ϵ depends upon the thermal contact between the calorimeter and its constant temperature environment.

The use of (1) with actual data requires averaging techniques to achieve the highest accuracy and precision. We reduce data for the BB 1 calorimeter by a least squares computer program. Also (1) contains all the quantities used in the computation of the energy equivalent E and is therefore the starting point for the analysis of errors in electrical calibration experiments.

Calorimetry compares laser energy actually absorbed to electrical energy. The energy in the beam as it strikes the calorimeter

is greater than the energy absorbed because of the small reflectance of the calorimeter proper. If W_i is the incident laser energy on the calorimeter that absorbs a fraction α , then the work quantity W in (1) is just αW_i .

Writing ΔT_c for the corrected temperature rise, we obtain the laser energy incident on the calorimeter in terms of observable quantities:

$$W_i = (E \Delta T_c) / \alpha. \quad (3)$$

The determination of the energy in the laser beam depends on the determination of the three quantities on the right of (3). This equation contains all the quantities required to compute the energy from a laser beam and is therefore the starting point for the analysis of errors in laser energy measurements.

The temperature of the surroundings was not held constant. To estimate the consequences of this for this calorimeter we estimate that its temperature T is given by the equation

$$T = T_R + P/h + Me^{-h\epsilon t/E} \quad (4)$$

where T_R is the temperature of the calorimeter's environment, P the power delivered to the calorimeter by the pump, and h is such that $(T - T_R)/h$ is the power flowing out of the calorimeter due to the temperature difference between it and its surroundings. We have assumed in deriving (4) that the calorimeter has a single temperature associated with it. While this is not exactly the case, it is not a serious flaw for the use we intend to make of (4).

After the calorimeter had been cooled off to its low-temperature range the pump was turned on and the temperature was read at equal time intervals until the calorimeter's temperature had reached its upper temperature limit. This took about 4½ h. This data of temperature (volts) versus time was fitted by a computer program by least squares to a second degree polynomial. By comparing the zeroth-order term, the first derivative, and the second derivative of (4) and the polynomial, we find that

$$P = 583 \text{ W}$$

and

$$h = 53 \text{ W/V}.$$

To obtain these values we had to use our experimentally determined value for E . We note that a 1-V change from our electrical thermometer corresponds to a temperature change of 12°C and that our maximum temperature range was from -2 to +2 V. Room temperature was about -0.5 V. One sees that if there was a change in the room temperature of about 0.5°C, this would cause a change in the heat flow in or out of the calorimeter by approximately 2 W. This would contribute a negligible effect except when the input electrical or laser power becomes small. At 300 W this possible effect is less than 1 percent.

V. ELECTRICAL CALIBRATION

There are two independent sets of heaters in BB 1 calorimeter. One heater, the tank heater, was placed in the water

reservoir. The other heater, the rod heater, was placed around the optical cavity in the water jacket. A 10-kw dc power supply was used to supply the electrical energy used to determine the energy equivalent E for this calorimeter. The current through the heater was determined by measuring the voltage drop with a digital voltmeter across a standard resistor that was in series with the heater. The voltage drop across the heater was determined by bringing leads from a digital voltmeter into the calorimeter so that they were connected at about the midway point on the heater leads between the outer shell of the calorimeter and the heater connection. This helps to reduce the systematic error associated with heater leads.

The digital voltmeters were calibrated by comparison to a standard cell and the standard resistor was calibrated by the RF Power, Current, and Voltage Section of NBS. The digital voltmeters read the average dc voltage. The power supply used did have an ac component in its output. For a dc current (average current) of 10.7 A the rms current of the ac component was 0.62 A. To compute the power delivered to the electric heater we took the product of the average voltage times the average current. Since this neglected the ac component we multiplied this result by 1.0035, which enabled us to include the power associated with this ac component. During the time the heaters were on, the voltages were read simultaneously every 0.3 s, and the readings were recorded by punching the information on paper tape. A short computer program computed the electrical power for each pair of readings and then took the average of the entire set.

The total time the power was delivered to the calorimeter was determined by a time-interval counter. The time scales on the time-interval counter used were checked by a known time signal supplied by the Time and Frequency Division of NBS. The time-interval counter was triggered by the voltage being applied to the heaters. The rise time of this signal is approximately 1 ms. Knowing the time interval and the average power delivered to the calorimeter, one can compute the total electrical energy delivered to the instrument.

VI. BACKSCATTERING

Part of the incident laser radiation is scattered back out of the calorimeter. To obtain a measure of this a special square calorimeter with a narrow slit in it was constructed. This square calorimeter was placed over the aperture of the BB 1 calorimeter. The narrow slit allowed one to pass a laser beam into BB 1 without striking the square calorimeter. The amount of backscatter was determined at a number of positions and at 1.06 and 10.6 μm . The backscatter varied from 0.1 to 2.4 percent. The average value of the observed value was 1.1 percent. Therefore, we have that α has the value 0.989. Because of the uncertainty of the beam size and profile, we feel that a systematic error of ± 1.3 percent should be associated with this value of α .

VII. PRECISION AND ACCURACY

Following the recommendations of Eisenhart [5] we present the systematic and random errors separately. The systematic errors in E due to systematic errors in V_h , V_r , t , and R is taken

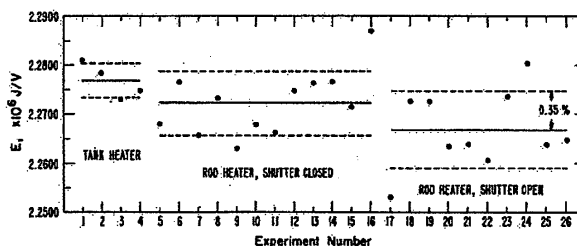


Fig. 3. Control chart showing calibration factor for BB 1 versus experiment number in chronological order.

to be

$$\frac{dE}{E} = \frac{dV_h}{V_h} + \frac{dV_r}{V_r} + \frac{dR}{R} + \frac{dt}{t}$$

where V_h is the voltage across the heater, V_r the voltage across the standard resistor, R the resistance of the standard resistor, and t the time the electric power is applied to the calorimeter. The systematic error in ΔT_c is taken to be zero [1] and therefore is not included in the preceding. Also, the systematic error associated with R and t can be neglected. The error associated with the voltage readings was less than 0.1 percent for one meter and 0.06 percent for the other. The systematic error due to the ac component is estimated to be less than 0.1 percent. Summing these systematic errors we obtain ± 0.26 percent as the limits to the systematic error in E .

A chronological control chart for the electrical calibrations of calorimeter BB 1 is shown in Fig. 3. The individual values of the energy equivalent are plotted in the order in which they were made. The average of the points is shown as a heavy dashed line. The estimated standard deviation for an individual measurement is about 0.35 percent and is plotted in the lighter dashed lines. The first four points were taken using the tank heater, and the next 12 points were made using the rod heater. For these 16 points the entrance to the calorimeter was covered. The last ten points were taken using the rod heater, and the shutter was open. Also, a slow flow of nitrogen was fed into the calorimeter. The nitrogen flows into the calorimeter when the shutter is opened to help to keep the optical surfaces clean.

In Fig. 4 the energy equivalent is plotted against energy input. Since there is no evidence of a significant trend, we believe that the linear theory holds in this range.

Fig. 5 is a control chart where the energy equivalent is plotted against the cooling constant. Again no significant trend is observed. The cooling constant varies because the rating period to determine the cooling constant is only about 5 min long while $(1/e)$ is about 10^3 min. Thus, a small error in the determination of the slope during the rating period extrapolates to a much larger effect in determining ϵ .

It was felt that the value for E that should be used is the one obtained with the shutter open and nitrogen flowing. The average value of these ten points is 2.267×10^6 J/V. The standard deviation is 0.008×10^6 J/V. The percent standard deviation is 0.35 percent.

We need to consider the systematic error due to the geo-

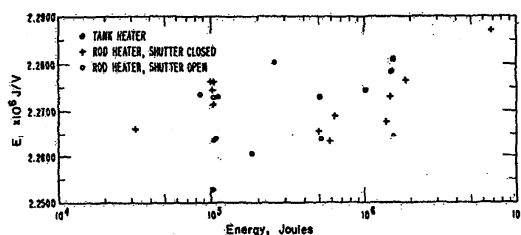


Fig. 4. Control chart of the calibration factor for BB 1 versus energy.

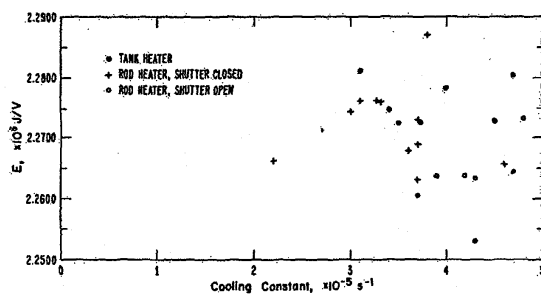


Fig. 5. Control chart of the calibration factor for BB 1 versus the cooling constant.

metric effect that is a result of the fact that two heat sources in the calorimeter have different interactions with the environment and thus produce different effects upon the calorimeter. This error is decreased as the two sources are made remote from the surface of the calorimeter and the heat exchange is made small. The two heaters in BB 1 are located at different

positions, but both are submerged in the water. The difference between the average value for these two heaters is about 0.2 percent.

The laser radiation will be absorbed on the surfaces of the optical cavity. In some cases these surfaces will be heated to relatively high temperatures. While most of the thermal radiation emitted will be reabsorbed, some will escape back out of the entrance horn. The optical cavity was designed to reduce this effect by making the opening of the calorimeter small compared to the total surface area and by designing the calorimeter to minimize the temperature rise. We estimate this systematic error to be ± 1.0 percent. However, in some power levels it could be greater. We do feel that this is probably reasonable for most of the power range for which this instrument is designed. Combining these three errors we obtain a total estimated systematic error of ± 2.6 percent.

We estimate the random error from the electrical calibration data. The percent standard deviation of 10 calibrations is 0.35 percent. This we will take as the estimation of the random error.

Therefore, we conclude that the energy equivalent of this calorimeter is 2.267×10^6 J/V. The total estimated systematic error is ± 2.6 percent, and the estimated random error is ± 0.35 percent.

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Measurement in the Submillimeter-Wavelength Region

JOHN CHAMBERLAIN

Abstract—A survey is given of current measurement activities at submillimeter wavelengths with particular regard to those carried out at the National Physical Laboratory. HCN and H_2O lasers and Fourier transform spectrometry form the basis of the techniques. Outlines of their application to measurements of the absorption and refraction of solids and liquids, the emission of atmospheric gases and plasmas, and reflection from lossy materials such as semiconductors are given. Frequency and wavelength measurements and their application to a determination of the speed of light are also discussed.

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The author is with the Division of Electrical Science, National Physical Laboratory, Teddington, Middlesex, England.

MEASUREMENT IN THE SUBMILLIMETER-WAVE REGION

THE development of far infrared or submillimeter-wave measurements began in earnest about 13 years ago, following the production of the first spectra obtained by Fourier transform methods [1]. The technology has advanced steadily rather than dramatically; (broad-band) spectrometric techniques have been refined to give high resolution quickly and many stimulated emission sources have been discovered, covering thinly most of the region between 0.3 and 3 THz. The radiation of these lasers has been applied to a number of measurement techniques [2].